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Review Article

Nanosilica: The Secret Ingredient for Enhanced Concrete Durability

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Abstract

This work compiles a series of investigations on the use of nanosilica (NS) as an additive in concrete, evaluating its impact on mechanical properties, durability, workability and sustainability. The studies consider the incorporation of NS in various proportions (0.4%-3%) and its combination with other additives such as microsilica and superplasticizers, using methodologies based on international standards (ACI, ASTM). The results show that NS significantly increases compressive strength (up to 56.92%) and flexural strength, improves impermeability and durability against aggressive environments, such as coastal and sulfated areas, by reducing the porosity of concrete. It is also observed that it optimizes workability in fresh mixtures, being ideal for self-compacting concretes. However, proportions above 1.5% can have adverse effects on cohesion and mechanical behavior. In terms of sustainability, the use of NS makes it possible to reduce the amount of cement needed, decreasing the carbon footprint of the material, and is considered economically viable in projects that prioritize durability and high resistance.

Keywords: nanosilica (NS), high-strength concrete, mechanical properties, concrete durability, permeability, workability, self-compacting concrete, nanomodified materials, innovation in construction.

Introduction

The incorporation of nanosilica in concrete mixtures has revolutionized the construction industry, significantly improving the mechanical properties and durability of the material. Recent studies have shown that the addition of nanosilica particles, in optimal proportions, can increase compressive strength, tensile strength, and other parameters crucial to concrete performance (Alvansaz, Bombon, et al., 2022) . In addition, the combination of nanosilica and polypropylene fibers has been shown to improve the durability of concrete, allowing it to be used in applications that require greater strength, such as rigid pavements. This approach not only optimises mechanical properties, but also promotes sustainability by enabling the use of recycled aggregates, which is essential in aggressive environments such as coastal or industrial areas (Amario et al., 2017).On the other hand, the analysis of different proportions of nanosilica in high-strength concrete mixtures has highlighted the need for rigorous control in its dosage. In mixtures with high-strength characteristics, the incorporation of 0.7% nanosilica can increase compressive strength by 21.71% compared to the standard design, while higher amounts can result in saturation that negatively affects the internal structure of the concrete (Yazdi et al., 2014).

In addition to the mechanical aspects, the seismic behavior of the structures is also influenced by the use of nanosilica. Recent studies have evaluated how lower structures exhibit higher levels of reliability in the face of seismic shocks, which is crucial for safety in earthquake-prone areas (Alvansazyazdi et al., 2023). On the other hand, the comparison between microsilica and nanosilica has added a technical and economic dimension to the use of additives in concrete. Both additions have proven effective in increasing the strength of the material; However, nanosilica, used in optimal proportions, can offer significant advantages in terms of performance and cost (Silvestre et al., 2016). The inclusion of silica nanoparticles in self-compacting concretes has proven to be an effective solution to improve both the rheological and mechanical properties of the material, optimizing its performance in both fresh and hardened states, which is especially beneficial in high-precision applications (Alvansaz, Arico, et al., 2022). In addition, the use of biocomposite materials, made from biomass and renewable resources, represents a significant advance in sustainable construction, offering a viable alternative to conventional materials as they are completely biodegradable under anaerobic conditions (Mohajerani et al., 2019).

Functionalization of nanosilica to confer hydrophobic properties has proven to be an effective strategy for improving the strength of concrete in aggressive environments, such as coastal and industrial areas. This approach allows nanosilica to accelerate the initial hydration of the cement, increasing the density of the cementitious matrix and reducing permeability, making it more difficult for aggressive agents such as chlorides and sulfates to penetrate (Vargas et al., 2024). In addition, it has been observed that the incorporation of silica nanoparticles improves the densification of the concrete microstructure, resulting in a material that is stronger and less susceptible to the penetration of water and corrosive agents, contributing to greater durability (Alvansazyazdi, Fraga, et al.).

The combination of microsilica and nanosilica has also been shown to be very effective in improving the mechanical properties and durability of the material. In this case, using a mixture containing 15% microsilica and 3% nanosilica significantly increases compressive strength by 23% compared to conventional pavers (Alvansazyazdi, Fraga, et al.). Likewise, the incorporation of up to 2% nanosilica has shown an increase of up to 141.57% in compressive strength at 28 days in concrete mixtures, highlighting the potential of this additive in improving concrete quality (Alvansazyazdi, Farinango, et al.). Finally, the combination of microsilica and nanosilica in high-performance mixtures has demonstrated a significant improvement in mechanical strength, especially in compressive strength, which increased by up to 28% at 28 days compared to conventional mixtures (Gesoglu et al., 2016).

Development

The integration of nanosilica and polypropylene fibers in concrete has made significant advances in its mechanical and hydraulic properties, especially for rigid pavement applications, using recycled aggregates along with Portland Type I cement and admixtures that comply with regulatory standards, thus ensuring the structural performance of the material (Swilam et al., 2024). Nanosilica increases compressive strength from early stages, improving the durability of concrete and reducing its permeability, allowing greater resistance to degradation by external factors (Leiva Manchego, 2022).

Polypropylene fibers, on the other hand, increase the flex, ductility, and toughness of concrete, making it able to withstand high loads before fracturing(Banthia & Sheng, 1996) . A detailed analysis of nanosilica ratios in high-strength concrete mixes shows that an addition of 0.7% can increase compressive strength by 21.71% compared to the standard design, while higher percentages, such as 1.0%, can decrease strength due to saturation of the mixture (Farjad, 2024).

The comparison between microsilica and nanosilica reveals that, in optimal proportions, nanosilica can increase compressive strength by 51.32%, while microsilica provides more consistent improvements in terms of overall performance and cost-benefit (Sanchez Chicana, 2024). The incorporation of silica nanoparticles in self-compacting concrete improves its rheological and mechanical properties, optimizing its performance in both fresh and hardened states, with increases of up to 25% in compressive strength after 28 days (Faraj et al., 2023). In addition, the combined use of nanosilica and nanoalumina has shown improvements in the durability of the material, increasing the compressive strength by up to 16.42% and reducing the air content in the mixture, which contributes to greater impermeability(Raveendran & Vasugi, 2024) .

The combination of nanosilica as a partial substitute for cement and rock wool as a substitute for coarse aggregate in concrete mixtures has led to a significant advance in the sustainability of construction materials, achieving increases of 21.85% in compressive strength and a reduction in air content in mixtures with 1.4% nanosilica and 6% rock wool (Nicolle Bravo et al., 2024). In conventional mixtures, the addition of 1.3% nanosilica showed increases of 47.79% in compressive strength and 36.36% in modulus of rupture, also improving workability (Sanchez Chicana, 2024). For deep foundations in high water table conditions, strengths of up to 434.4 kg/cm² were achieved with 0.50% nanosilica, controlling bleeding and reducing the temperature of the concrete(Reese et al., 2005) .

In self-compacting concretes, a dosage of 1.7% nanosilica achieved a strength of 704.20 kg/cm², optimizing the proportion of materials and reducing the water content by 19.26%(Dehn et al., 2000) . The durability of concrete in sulfated environments was improved with 1% nanosilica, reaching 395 kg/cm² after 28 days and minimizing the penetration of harmful agents (Abhilash et al., 2021). In addition, in high-strength mixtures, increases of 12.70% in compressive strength were achieved with 0.7% nanosilica, showing improvements in workability and cohesion (Ccanto Rivera, 2021). The combination of nanosilica and microsilica in suitable proportions allows obtaining strengths above 900 kg/cm², optimizing mechanical properties and reducing costs in modern construction (Saavedra Pérez, 2019).

In coastal regions, where conventional concretes face constant threats from the action of sulfates and chlorides, nanosilica has emerged as an indispensable alternative to improve the durability of structures, achieving a compressive strength of 391 kg/cm² after 42 days with an addition of 1.5% of nanosilica in mixtures with type I and V cements. even after prolonged exposure to seawater. in addition to reducing porosity to values below 1.70% (Bernal et al., 2018). The combination of ground glass and nanosilica in concrete mixtures showed a 64.7% increase in sedimentation, improving workability, albeit with a 13.4% increase in production costs (Abhilash et al., 2021). In high-strength mixtures that incorporate superplasticizers together with nanosilica, strengths of 826.51 kg/cm² were achieved after 28 days with 1.0% of both additives, optimizing the water/cement ratio and improving fluidity (Plank et al., 2015).

A comparative analysis between microsilica and nanosilica revealed that while 10% microsilica significantly improves strength, 1.5% nanosilica achieves similar results at lower costs, reaching up to 964.73 kg/cm² in suitable combinations (Bheel et al., 2024). In addition, concrete combining recycled aggregates with 1.5% nanosilica showed a 39.33% increase in compressive strength, addressing environmental issues and offering a cost-effective alternative for sustainable projects (Elkady et al., 2013). The combination of these additives reinforces the production of stronger, more durable and sustainable concretes, addressing modern challenges in construction and promoting the circular economy (Asto Quispe & Quiroz Flores, 2021). It has been shown that the use of nanosilica in mixtures with type I and IP cement improves mechanical strength by 12.70% with 0.7% additive, optimizing costs and improving cohesion and workability, positioning nanosilica as a strategic solution in the construction industry (Rondo Rojas, 2021).

The combination of nanosilica with microsilica in concrete mixtures has proven to be a versatile solution to improve specific properties such as compressive strength, tensile strength and bending, especially in high-demand applications, reaching up to 920.33 kgf/cm^2 with 10% microsilica and 1.5% nanosilica. This adjustment of the ratios is crucial to avoid saturation and ensure efficient performance. Improved mechanical properties offer high potential for heavy infrastructure projects and high-strength pavements, where the use of sustainable materials is essential (Uriarte Rubio, 2022). In addition, the use of recycled aggregates with 1.5% nanosilica increased compressive strength by 39.33%, evidencing that these materials can effectively replace traditional ones without compromising structural properties, which is relevant to reduce construction waste (Osorio Pedraza, 2019). The combination of ground glass and nanosilica, with 5% glass and 1% nanosilica, improved workability by 64.7% and decreased air content, although it increased production costs, requiring a careful balance between technical and economic benefits (Neyra Cruz, 2023).

These studies show that the use of additives such as nanosilica, microsilica and recycled aggregates not only improves the properties of concrete, but also addresses environmental and economic challenges, contributing to a more sustainable future in construction (Ayala Aguilar & Ccallo Perez). The inclusion of nanosilica in combination with fly ash has proven to be a strategic solution for small businesses, as it improves strength without affecting workability and reduces water consumption, although the impact on costs is variable (Bheel et al., 2024). In the design of high-performance concretes, the use of different percentages of nanosilica has demonstrated significant improvements in mechanical strength, allowing an optimal balance between strength, durability and workability (Chuzón Villacorta & Ramírez Guevara, 2020). The combination of nanosilica with specific aggregates has achieved strengths of up to 520.30 kg/cm^2 at 28 days, optimizing performance against adverse environmental conditions and offering a technical and sustainable solution for demanding structural applications (Gunasekara et al., 2020).

The development of new technologies such as the use of nanosilica, microsilica, ground glass, superplasticizers and recycled aggregates has allowed the construction industry to face challenges such as durability, resistance, sustainability and economics. These combined technologies optimize the properties of concrete, improving its physical and mechanical performance, while addressing environmental and economic issues, positioning them as key solutions for the future of construction(Vargas et al., 2024). The incorporation of nanosilica in type I and V cement has shown an increase in compressive strength to 922.67 kg/cm^2 after 28 days, in addition to improving chemical resistance to aggressive environments, such as saline soils and salt water, making it an ideal option for coastal areas and high durability projects (Han et al., 2021). The combination of nanosilica with microsilica and superplasticizers has optimized both mechanical properties and workability, reaching strengths of up to 740 kg/cm^2 after 28 days and facilitating the efficient application of concrete (Aıtcin, 2003).

Figure 1. Concrete with the addition of nanosilica and superplasticizer

In areas with high exposure to corrosive agents, such as coastal areas, the use of nanosilica with V-type cement has increased durability and reduced porosity, reaching strengths of up to 395 kg/cm^2 after 42 days in salt water, making this combination ideal for maritime and infrastructure projects (Gonzalez, 2014). The inclusion of frosted glass with nanosilica improves the workability and density of concrete, while promoting sustainability through the recycling of industrial waste, contributing to the circular economy (Pavlík & Užáková, 2016).

Finally, the use of nanosilica with recycled aggregates has proven to be a viable and technically sustainable option, increasing compressive strength by 39.33% and reducing environmental impact by decreasing the need for extraction of new natural resources (Saba et al., 2023). In short, these innovations not only balance costs and technical properties, but also address the challenges of sustainability and the circular economy, positioning these approaches as key practices for the future of civil engineering(Adamu et al., 2024).

Table 1. Summary Table of Nanosilica Mixtures and Their Benefits

Technology / Additions	**Advantages**
Silica nanoparticles	Improves the compressive strength of concrete.
Nanosilica + Superplasticizers	Up to 56.92% increase in compressive strength. Reduction of water consumption by up to 42%.
Nanosilica + Microsilica (1.5% + 10%)	Resistance of up to 900 kg/cm2 after 28 days. Improves durability by reducing voids
Nanosilica + Recycled Aggregates	Increases stamina by up to 39.33%. Dependence on natural resources decreases.
Nanosilica + Frosted Glass	64.7% increase in workability. Improves density and durability.
Nanosilica + V-type cement	Increases compressive strength up to 395 kg/cm2. Reduces porosity and improves protection against sulfates.
Nanosilica + Fly ash	Improves cost-benefit in high-performance blends. Improves mechanical properties and durability.

Observations and discussions

This addition significantly improves the durability and mechanical properties of the material, especially when combined with type I and type V cement, increasing compressive strength and chemical resistance to aggressive environments, such as soil and salt water [43]. However, the challenge lies in the need to optimize the nanosilica dose to ensure consistency in the results, as a poor ratio could affect the performance of the mixture. The combination of nanosilica with microsilica and superplasticizers has also proven to be effective, not only in terms of strength, but also in improving the workability of concrete, making it easier to apply on high-performance sites. However, the costs associated with these additives could be a limiting factor, especially in large-scale projects, so it is necessary to assess their economic viability according to the specific needs of each project [44].

On the other hand, the use of frosted glass and recycled aggregates, combined with nanosilica, not only improves the strength and density of concrete, but also contributes to sustainability by recycling industrial materials and reducing environmental impact. However, the durability of these mixtures under extreme exposure conditions still needs to be further evaluated to ensure their long-term efficacy [45]. Finally, the use of recycled aggregates together with nanosilica offers an economical and sustainable solution, especially in urban infrastructure and social housing projects, although it is essential to continue investigating their behavior under severe conditions, which will ensure their applicability in large projects in the long term [46]. These emerging technologies, which combine nanosilica with recycled materials and other advanced additives, constitute a promising alternative to address the challenges of durability, sustainability and efficiency in the construction industry [47].

Conclusions

In conclusion, the use of nanosilica has emerged as one of the most effective solutions to improve the durability of concrete, positioning itself as a key additive to face the current challenges of the construction industry. Its ability to act as a pozolanic agent improves the microstructure of concrete, reducing porosity and increasing its density. This characteristic not only strengthens the mechanical properties of concrete, such as compressive strength, but also increases its chemical resistance to aggressive environments, such as saline soils and seawater. Tests have shown that the addition of nanosilica, even in small amounts, can significantly increase the durability of the material, making it an ideal choice for projects that require high corrosion resistance, especially in coastal areas or in structures exposed to severe weather conditions.

In addition, the versatility of nanosilica in combination with other additives such as superplasticizers and ground glass allows the creation of high-performance concrete mixtures, optimizing both workability and efficiency in their application. Through these combinations, a concrete with greater cohesion, lower porosity and greater resistance to corrosive agents is achieved, which translates into a more durable and sustainable material. By integrating nanosilica into the design of concrete mixes, a technically and economically viable solution is obtained that not only meets the requirements of strength and durability, but also contributes to sustainability through the use of recycled additives and the reduction of environmental impact, consolidating its essential role in the future of construction.

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